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Fuzzy Computing for Control of Aero Gas Turbine Engines

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ABSTRACT

Many methods, techniques and procedures available for designing the control system of plants and processes, are applied only after knowing accurately the plant or process to be controlled. However, in some complex situations where plants/processes cannot be accurately modelled, and especially where their control has human interaction, controller design may not be completely satisfactory. In such cases, it has been found that control decisions can be made on the basis of heuristic/linguistic measures or fuzzy algorithms.

Fuzzy set principles have been used in controlling various plants/processes ranging from a laboratory steam engine to an autopilot, including an aero gas turbine engine for which the response of the engine speed for a fuzzy input of fuel flow has been studied. In this paper, certain stipulations and logic are suggested for the control of the total gas turbine engine. A case study of a single spool aero gas turbine engine with one of its state variables varied by heuristic logic is presented.

NOMENCLATURE

ISA	International standard atmosphere
JPT	Jet pipe temperature
N	Engine rotational speed
NB	Negative big
NM	Negative medium
NS	Negative small
PID	Proportional, integral and derivative
PLA	Power lever angle
P2	Compressor outlet pressure
P3	Combustor outlet pressure/turbine inlet pressure
P4	Jet pipe pressure
PB	Positive big
PM	Positive medium
PS	Positive small
SLS	Sea level static condition
T2	Compressor outlet temperature
TET	Turbine entry temperature
WF	Dimensional fuel flow

δ = Correction ratio for pressure variation = ambient atmospheric pressure/atmospheric pressure ISA, SLS

θ = Correction ratio for temperature = ambient atmospheric temperature/atmospheric temperature ISA, SLS

1. INTRODUCTION

A number of methods, techniques and procedures are available in the existing control theory that can solve

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a large variety of problems involving control system design and analysis. Multivariable control, optimal control, adaptive control, self-tuning regulators, and state estimation techniques are some methodologies/approaches that are available and belong to this class. In all these, there is a basic requirement to know accurately the model of the plant or the process to be controlled so that a controller can be suitably designed. In some complex situations, where the plant cannot be accurately modelled, controller design may be entirely unsatisfactory resulting in improper control of the plant. While this is the case invariably with plants/processes where human interaction for their control is required, it is found that control decisions can be made on the basis of heuristics or linguistic measures resulting in a better predictable control of the plant/process. This deployment of heuristics/linguistic measures forms the basis of fuzzy control, the foundation for which is laid by Zadeh in his theory of fuzzy sets[1-3].

Using fuzzy set theory (FST), information available in qualitative form is used to control the plant/process. Fuzzy set theory provides a technique to handle this qualitative information. The controller that is designed on the basis of this theory is called fuzzy logic controller.

2. PREVIOUS APPLICATIONS OF FUZZY LOGIC IN PLANT CONTROL

In his approach Zadeh provides a method of expressing linguistic rules that can include a strategy or protocol, based on which the plant can be controlled in different situations. Using linguistic variables, a control algorithm is constructed. Some typical plant applications where this approach is made use of are illustrated in the following:

Mamdani and Assilian[4] have described how a plant comprising a steam engine-boiler combination is controlled by a fuzzy controller. They have brought out a comparison of the responses obtained between a fixed digital controller and a fuzzy controller.

Various industrial applications of fuzzy logic control are mentioned by Larsen[5]. He has made particular mention of its use in a rotary cement kiln.

Details of a heuristic controller for dynamic processes are presented by Procyk and Mamdani[6], wherein the control policy can develop and improve automatically. The controller's heuristics is in the form of a set of decision rules that are expressed quantitatively and manipulated by using the theory of fuzzy sets. This heuristic controller is termed as a self organising controller (SOC) because its control policy can change with respect to the process it is controlling and the environment that it is operating in. The feature of this controller is that it strives to improve its performance until it converges to a predetermined quality.

Ray and Majumder[7] have discussed the use of fuzzy logic control of a steam generating unit. They have shown the use of fuzzy logic controllers for feedback control of the decoupled non-linear steam generating unit.

The use of fuzzy logic control in a communication satellite is illustrated by Daley and Gill[8,9].

Li and Lau[10] investigated the possibility of using fuzzy algorithms in a microprocessor-based servomotor controller. They have also reported a comparison carried out among a PID controller, a model reference adaptive controller and a fuzzy controller. To achieve fast response and minimum steady state error, the quantisation of the parameters for a fuzzy controller is so arranged that the full lookup table is utilised. Also, the authors used two sets of algorithms, one for coarse control and the other for fine control. This has helped in reducing the settling time.

A model of an autopilot controller based on fuzzy algorithms is described by Larkin[11]. The controller helps in manoeuvring the aircraft from level flight into a final approach flight path and maintains aircraft in glide path until just before touchdown. Flight simulation techniques are used to evaluate the performance and effectiveness of the model.

Wu Chi-Hua et al[12] have discussed the application of fuzzy control to the fuel control system of a turbojet engine. The control algorithm directly influences the engine control performance and a fuzzy type control is proposed as the control algorithm. They used a microcomputer to implement the function of the fuzzy controller and carried out the dynamic semi physical simulation test for the fuel control system of a turbojet engine. They applied a demand step signal of engine speed and showed how the fuzzy control algorithm gives out a fuel supply input to produce a speed output corresponding to the demand step signal of engine speed. They also showed that the demanded speed output is achieved within one second.

In the present paper, before arriving at a fuzzy control algorithm a certain amount of background work with fuel flow modulation based on turbine entry temperature datum is carried out. The available simulation model[13], validated with experiments has been utilised for this work.

3. FUZZY APPROACH IN AERO GAS TURBINE ENGINE: CASE STUDY

3.1 Classical/Crisp Set Applicability

In the classical or crisp set, the demarcation is such that the elements or individuals considered in the universe of discourse are divided into two clear categories. One category comprises elements that do not belong to a given universe of discourse and another category comprises elements that belong to same universe of discourse. Thus the definition of belonging is without doubt and is clear — a definite YES or a definite NO. In control system parlance, if a certain demand is placed, then a corresponding output would result with the demand and the output bearing a one-to-one correspondence. This is with the proviso that the controller guiding the plant parameters is so configured that it operates the plant in a safe and stable manner to the demanded position/requirement.

Extending this to an aero gas turbine engine application, for any demand placed by the pilot of the aircraft through the power lever angle (PLA) of the engine, the appropriate thrust is generated by the engine to enable forward movement of the aircraft. Therefore, for every position of the PLA, a unique value of the control variable, say fuel flow, is generated which enables the production of the corresponding thrust. Thus, in this case, a correspondence exists between the PLA, the fuel flow and the thrust. For a typical aero gas turbine engine, this correspondence has to be worked out and maintained over the entire flight envelope of the aircraft. If there are more number of control variables, the correspondence functions have to bear applicable multirelationships. Besides, if some of the elements in these correspondences have to be excluded so as to enable safe and reliable operation of the engine, the algebra of these correspondences has to be suitably worked out and incorporated. Using this as a basis, the next section describes an approach in relation to an aero gas turbine engine.

3.2 Outline Based on Set Theoretic Approach for Aero Gas Turbine Engine Control

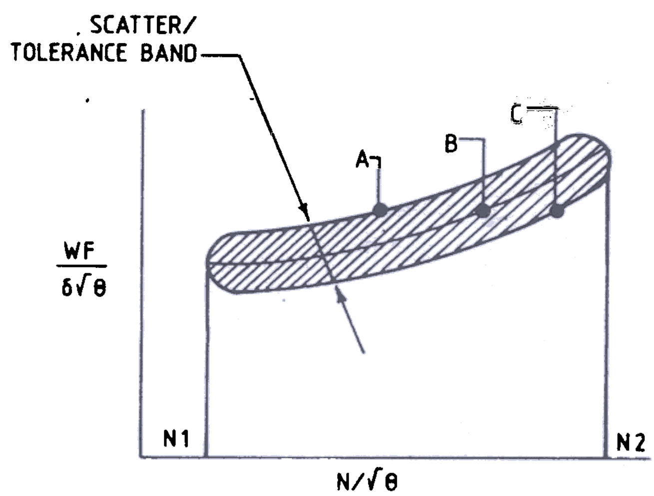
This case study proposes to focus attention on the total performance and requirements for control of the aero gas turbine engine. In the aero gas turbine engine, there are three control mode areas on which attention is to be focussed:

(a) Steady state control mode, wherein the engine is required to be maintained within an acceptable tolerance band of performance.

(b) Transient control mode, wherein the engine is required to reach the demanded steady state with no abnormal overshoots, within acceptable steady state error and within stipulated response times.

(c) Limit control mode, wherein the engine is required to operate safely and reliably within the limits laid down in respect of various engine sub-systems and engine state variables.

It is proposed to visualise the steady state and the transient control modes in terms of domains of fuel flow schedules as brought out in Figs. 1, 2 and 3. The fuel flow schedules brought out in these figures are corrected values. They outline the limits on steady state schedule, acceleration schedule and deceleration schedule, respectively. The tolerance band for the steady state engine performance is also brought out. Further, the limits in schedule to avoid possible surge and flame out are also indicated.



CURVE A UPPER BOUND

CURVE B STEADY STATE SCHEDULE

CURVE C LOWER BOUND

Figure Steady state domain of performance.

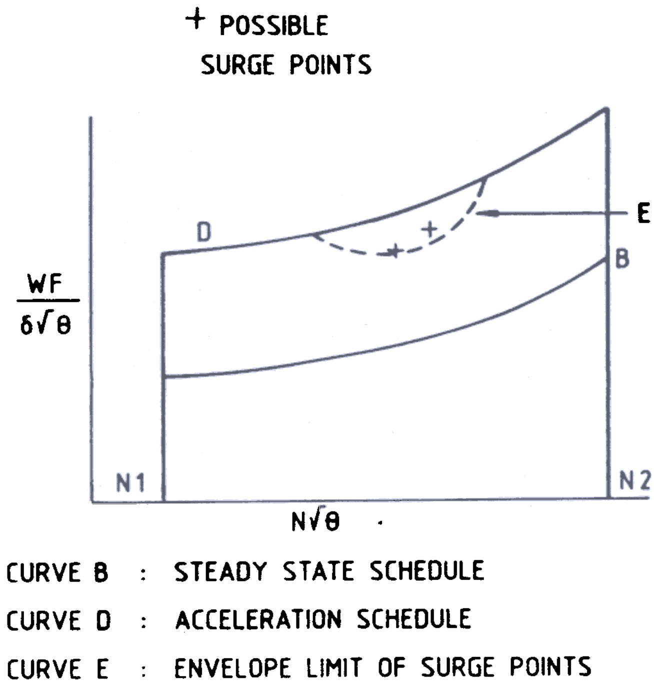


Figure 2. Acceleration domain of performance.

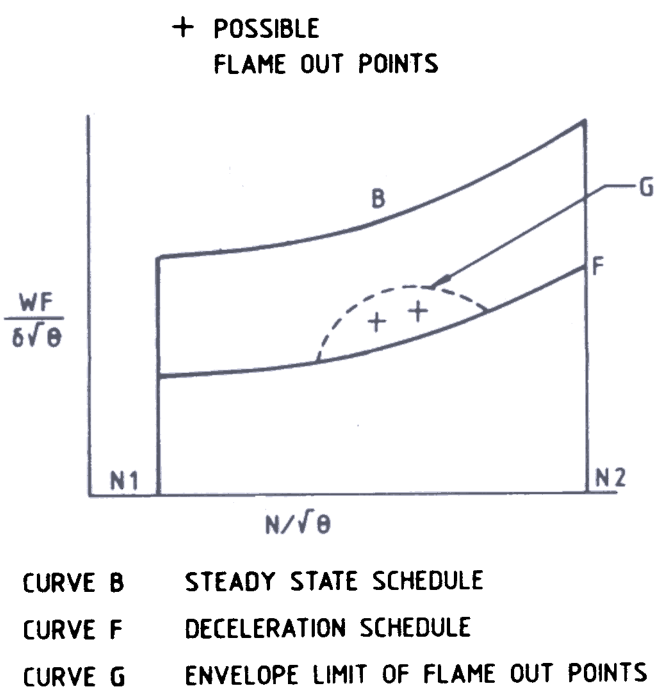


Figure 3. Deceleration domain of performance.

The domains of performance can be reckoned over the universe of discourse, i.e., the designated range of operation of engine rotational speed from $N1$ to $N2$. Under steady state conditions of the engine rotational speed range $N1$ to $N2$; A, B and C (Fig. 1) can be considered as sets of fuel flows.

Where

$$\begin{aligned} &\text{Set A:} && \{a_1, a_2, \quad a_\infty\} \\ &\text{Set B:} && \{b_1, b_2, \quad .b_\infty\} \\ &\text{Set C:} && \{c_1, c_2, \quad c_\infty \end{aligned} \tag{1}$$

Further,

Curve A = Upper bound of steady state fuel flow scnedule

Curve B = Steady state fuel flow schedule

Curve C = Lower bound of steady state fuel flow schedule

In the steady state control mode of operation, the domain of performance that is of interest is

$$\text{Set A} - \text{Set C} \tag{2}$$

Expression (2) would enable the fuel flow to be scheduled within the specified tolerance band, i.e., within the lower and upper bounds resulting in acceptable engine speed and/or engine thrust under steady state conditions.

In the transient control mode of operation for acceleration, D is the set of elements that defines the acceleration limit and E is the set of elements that would describe the surge points in the engine. These surge points will have to be avoided during acceleration throttle slams. Therefore, the acceptable acceleration domain of performance would be

$$(\text{Set D} - \text{Set B}) - (\text{Set D} - \text{Set E}) \tag{3}$$

Where

$$\text{Set D} = \{ d_1, d_2, \ldots\ldots d_\infty \}$$

$$\text{Set E} = \{ e_1, e_2, \quad .e_\infty \}$$

Further,

Curve D = Acceleration fuel flow schedule

Curve E = Envelope limit of fuel flows above which surge occurs (Fig. 2)

To accelerate the engine from speed $N1$ to speed $N2$, overfuelling is essentially required. However, this needs to be controlled so as to avoid not only compressor surge but also unacceptable overtemperatures. The required acceleration times are also to be met with. Expression (3) should cater for these factors.

In the transient control mode of operation for deceleration, F is the set that defines the deceleration limit and G is the set that stipulates the flame out points. Hence the acceptable deceleration domain of performance would be

(Set B – Set F) – (Set G Set F) (4)

Where

Set F = $\{f_1, f_2, ...f_\infty\}$

Set G = $\{g_1, g_2, ...g_\infty\}$

Further,

Curve F = Deceleration fuel flow schedule

Curve G = Envelope limit of fuel flows below which flame out occurs (Fig. 3)

To decelerate the engine from speed $N2$ to $N1$, obviously underfuelling is required. Rapid underfuelling may tend to a flame out of the engine which should be avoided. The required deceleration times are also to be met with.

To incorporate the limit control mode, the limits of the various engine state variables should be expressed in terms of the basic control variable, i.e., fuel flow rate in this case. The set of these fuel flow rates which causes exceedance of the engine state variable should be deducted from the gross expressions (2), (3) and (4) so that safe and reliable operation of the engine is ensured.

The above domains of performance for the engine are governed by the fuel control sets defined in expressions (1), (2), (3) and (4) above.

3.3 Illustration of Fuzzy Set *vis-a-vis* Classical Set

An example of n students in a class with their heights is considered. For the n students there would be n measurements of height. As per conventional set theory, each one of the n students belongs to or does not belong to the given measurement of height. On the other hand, fuzzy set theory helps in visualising the student as belonging to any measurement on the basis of a membership value varying from 0 to 1. The details of this example are discussed in Appendix I.

3.4 Considerations in Heuristic Approach

The elements in any given control set can be ascribed by a weightage or membership function so that the output of the sets under consideration can take cognizance of the same. Further, the outputs from these control sets can also be spelt out in terms of linguistic measures, such as positive small (PS), positive medium (PM), positive big (PB), negative small (NS), negative medium (NM), negative big (NB), etc. The control algorithm can then be based on this as given in Ref. 12. The algorithm in Ref. 12 prescribes a heuristic method of providing fuel flow input to achieve the demanded rotational speed in a single-spool turbojet engine. For a demanded speed, a fuel flow input is given and, in the transient, the correction in fuel flow is modulated at every computational instant based on the instantaneous error between demanded speed and achieved speed and also the rate of change in this error. This error and error change rate are prescribed heuristically, such as, PB, PM, PS, etc., and the correction in fuel flow for each one of these combinations of error and error change rate is also prescribed heuristically, such as PB, PM, PS, NB, NM and NS.

3.5 From Crisp to Fuzzy Set for Aero Gas Turbine Engine Control

In the crisp set or classical approach, the individual elements in the given universe of discourse are classified strictly into two categories, i.e., members belonging to and members not belonging to the set. The membership function in these cases can be considered as 1 and 0, respectively. In the fuzzy approach, this transition from 1 to 0, i.e., from member to non-member, is made gradual rather than a step change. That is, for the elements in the given universe of discourse, each element has a membership function of 100 per cent (i.e. 1) at its own location and has a membership function reducing to 0 per cent (i.e. 0) in any prescribed manner at all other locations away from its own location. A fuzzy set is defined mathematically by assigning to each possible element in the universe of discourse, a value representing its grade of membership in the fuzzy set.

In essence, the fuzzy set approach imbibes multivalued logic. Its ultimate goal is to provide approximate reasoning with imprecise or heuristic propositions. The elements in the universe of discourse are quantised into heuristic measures, such as PB, PM, PS, NB, NM and NS to bring out their relationship with respect to a nominal value. From the literature outlined in Section 2, Ref. 12 brings out the particular application in relation to a turbojet engine. This study shows the response of engine speed to a fuzzy variation in the fuel flow input. This fuzzy variation of the input fuel flow is based on the following:

(a) Instantaneous error between demanded value of the engine speed and actual value of the engine speed at any instant.

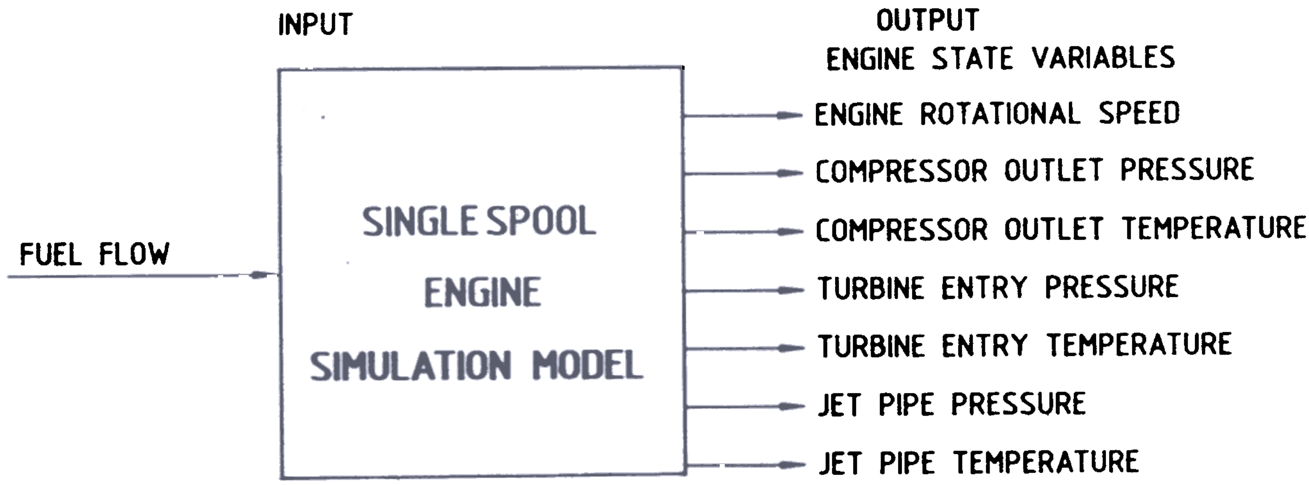
(b) Instantaneous change in error or error-dot of the engine speed between the present instant and the previous instant.

This error and error-dot are quantised into linguistic measures as outlined earlier. Any combination of these defined at any instant of time is converted into a control requirement, i.e., that of fuel flow input which is also specified heuristically.

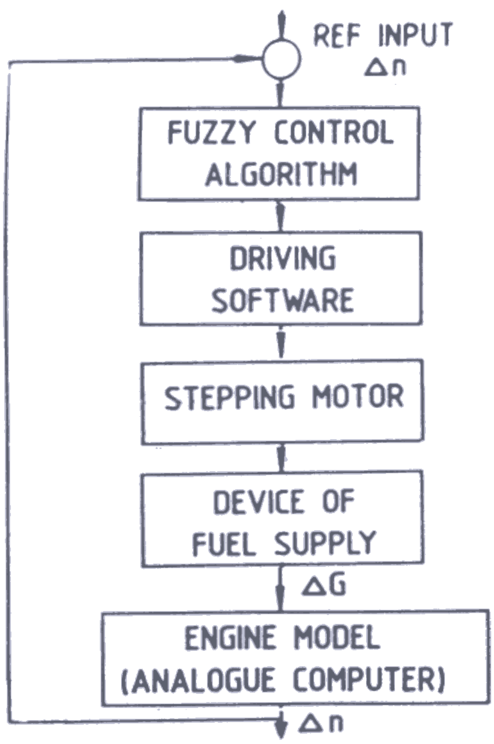
3.6 Fuzzy Controller on Heuristic Basis

In a typical single-spool aero gas turbine engine cycle, there are various engine state variables to be considered. These comprise engine rotational speed, compressor outlet pressure, compressor outlet temperature, turbine entry pressure, turbine entry temperature, jet pipe pressure, jet pipe temperature, etc. These are illustrated in Fig. 4(a).

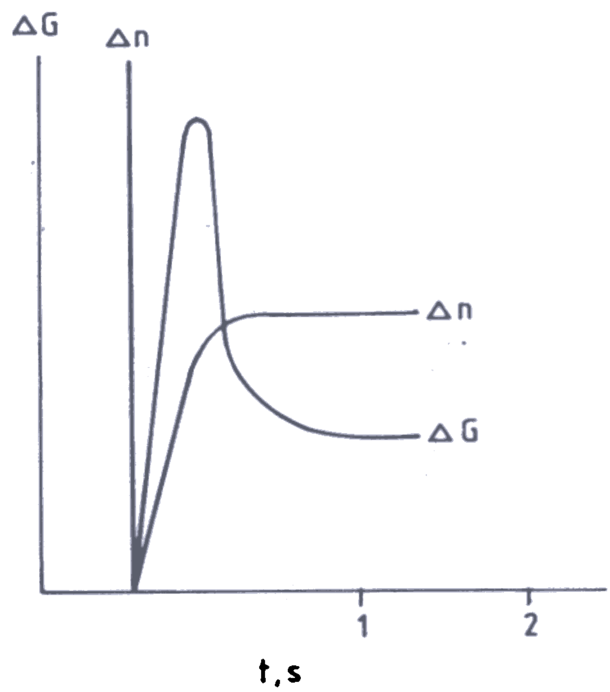
Figure 4(b) taken from Ref. 12 brings out the block diagram of fuzzy implementation in an engine program. Figure 4(c) shows the variation in fuel flow through a



4(a)



4(b)



4(c)

Figure 4. (a) Typical engine state variables in a single-spool engine, (b) block diagram of fuzzy implementation in an engine programme, and (c) response for reference step input.

fuzzy implementation and how the desired response in engine speed is obtained. In the present study, the effect of fuel flow on engine state parameters like turbine entry temperature (TET) is also considered while predicting the engine speed response. TET is considered as it is the highest temperature in the engine cycle and has a direct influence on the turbine blade life and consequently the engine health. Therefore, in the present study, for a step input in fuel flow, the TET transient is monitored. This step input is suitably varied over the nominal value, so that exceedances in TET are kept to a minimum, while the engine speed reaches the desired demand value within a response time of about 1.0 s. This forms the basis for the TET datummed logic.

The block diagram incorporating the fuel flow input, the engine model and the TET datummed logic is shown in Fig. 5. The error in TET is input into a TET datummed logic block that works out a correction value of the fuel flow. This corrected value is fed into the loop.

For the purpose of comparison, from an available simulation program with step input of fuel flow[13], the responses of engine state variables, such as engine speed, compressor delivery pressure, turbine entry temperature; jet pipe temperature and thrust for a step input in fuel flow, are determined. The individual responses are brought out in Figs. 6, 7, 8, 9 and 10, respectively. The percentage overshoot, especially in respect of TET, is of the order of 1.4 per cent over the steady state value at 100 per cent. Subsequently, the response for variation of fuel flow based on TET datummed logic is also obtained. This is superimposed in the same figure.

The comparison shows that the overshoot in the critical cycle parameter, TET, is contained within 3.2 per cent. At the same time the demanded speed is obtained within 1.1 s. The thrust buildup is also achieved within 1.0 s.

From the digital output results obtained with the TET datummed logic for the given fuel flow variation,

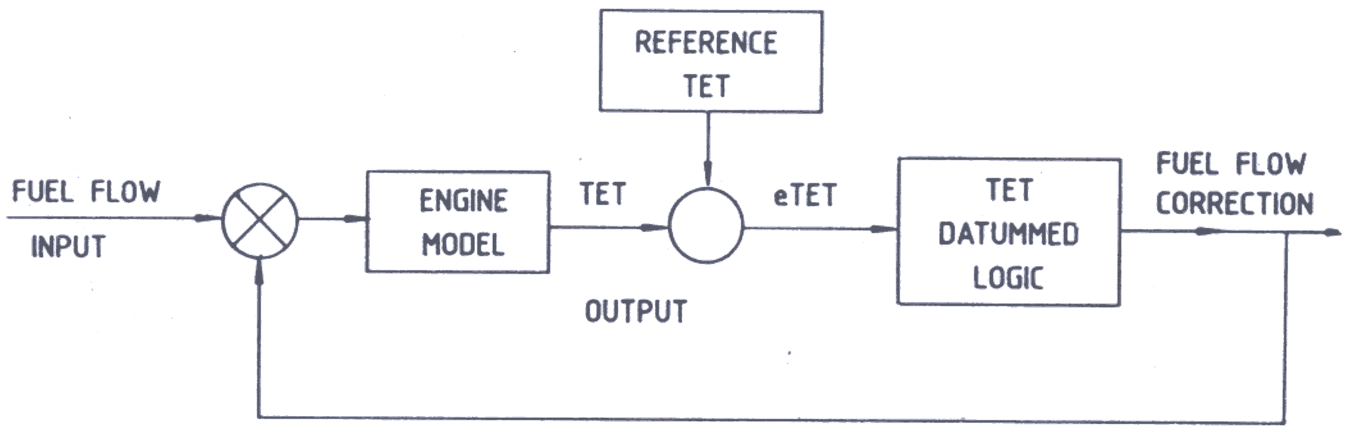


Figure 5. Block diagram incorporating TET datummed controller.

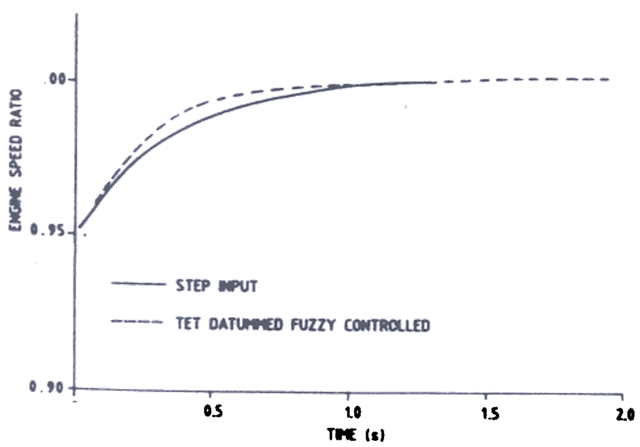


Figure 6. Time response of engine speed ratio.

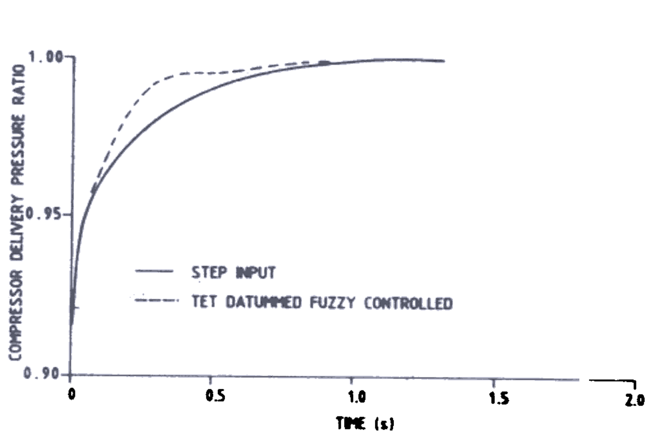


Figure 7. Time response of compressor delivery pressure ratio.

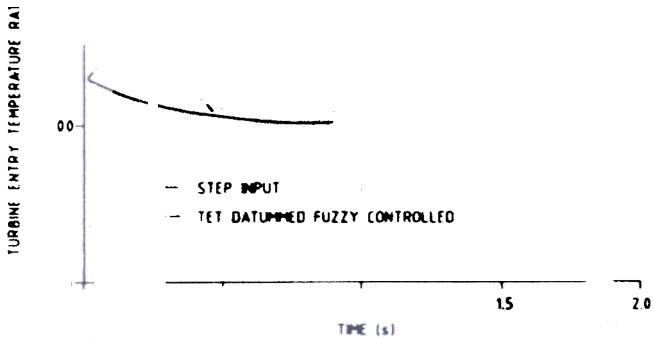


Figure 8. Time response of turbine entry temperature ratio.

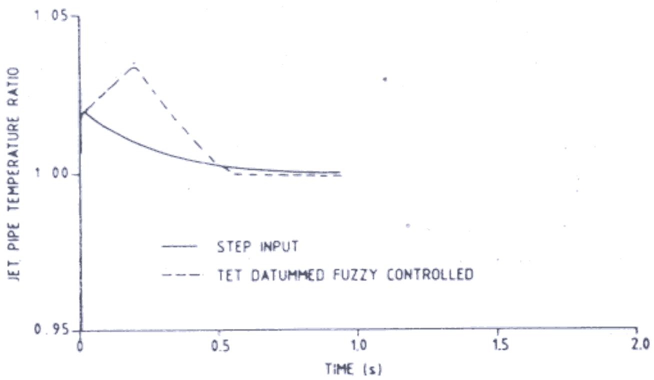


Figure 9. Time response of jet pipe temperature ratio.

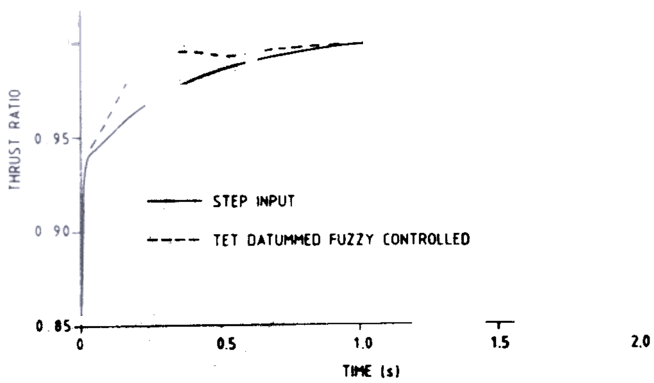


Figure 10. Time response of thrust ratio.

Table. Tabulations of fuel flow heuristic values for positive overshoots of TET

E-DOT / E	NB	NM	NS	PS	PM	PB
PB	PS	PS	PM	PM	PB	PB
PM	PS	PS	PS	PS	PM	PM
PS	PS	PS	PS	PS	PS	PS
NS	NS	NS	NS	NS	NS	NS
NM	NM	NM	NS	NS	NS	NS
NB	NB	NB	NB	NM	NS	NS

Table. 2 Tabulations of fuel flow heuristic values for negative overshoots of TET

E-DOT / E	NB	NM	NS	PS	PM	PB
PB	NB	NB	NB	NM	NS	NS
PM	NM	NM	NS	NS	NS	NS
PS	NS	NS	NS	NS	NS	NS
NS	PS	PS	PS	PS	PS	PS
NM	PS	PS	PS	PS	PM	PM
NB	PS	PS	PM	PB	PB	PB

the range of values of error and error-dot of the TET values is quantised and brought out in Tables 1 and 2. Corresponding to this quantised error and error-dot, a quantised correction value of the fuel flow is also brought out in these tables and a heuristic visualisation is illustrated. These tables would then form the basis of a fuzzy controller. The block diagram incorporating the TET datummed fuzzy controller is shown in Fig. 11.

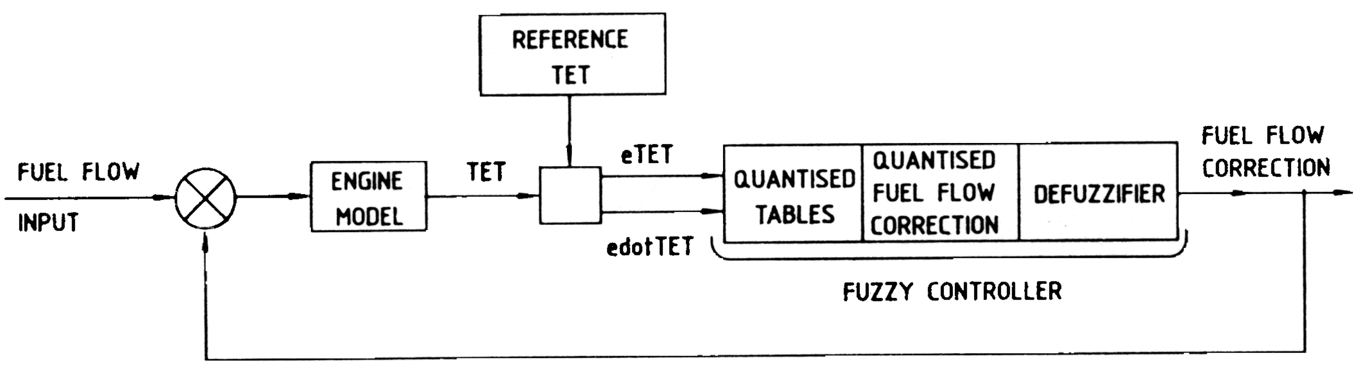


Figure 11. Block diagram incorporating TET datummed fuzzy controller.

4. CONCLUSION

The case study shows that with the TET datummed logic, a suitable variation of the control variable, i.e., fuel flow, has been able to contain the overshoot in the critical engine state variable, namely, turbine entry temperature within 3.2 per cent. This overshoot is slightly higher than what is obtained in an existing simulation program with step input of fuel flow. At the same time, the responses of the engine speed and the engine thrust to this TET datummed variation in fuel flow are comparable with the responses obtained from the existing program with step input of fuel flow. The present study shows that the TET datummed logic enables similar responses in terms of demanded speed and thrust to be obtained with negligible increase in turbine entry temperature when compared to the existing simulation program with step input in fuel flow. This simulation program has been validated with reference to experimental data from Orpheus engine tests.

This paper also brings out the method of visualising the TET datummed logic in the form of heuristic tables. As a next step, these tables are to be incorporated in the controller and the engine response compared with the response obtained using the error datummed and the existing programs.

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APPENDIX

ILLUSTRATION OF FUZZY SET *VIS-A-VIS* CLASSICAL SET

Suppose there are 20 children in a class with their heights varying from 1.5 m to 2.0 m in steps of 0.025 m. As per classical set, a student can belong to this set of heights only if his/her height falls in multiples of 0.025 m lying anywhere between 1.5 m and 2.0 m. For example, if a height of 1.53 m is stipulated, then there will be no student to satisfy this height, and classical set theory will clearly define this student as a non-member of this set.

In the case of fuzzy set approach, every height from 1.5 m to 2.0 m in steps of 0.025 m is termed as the universe of discourse. Each of these heights commands a membership function value of 1.0 corresponding to the

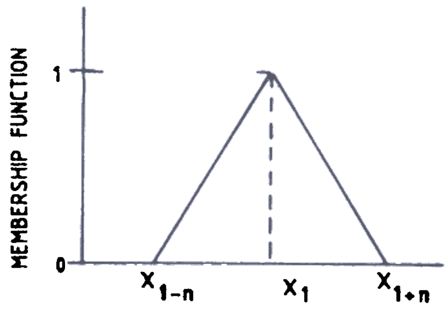

Fig. A1

particular student. If a height or the student corresponding to this height is to be referred to at any height, the membership function value will reduce and become zero, the farther it is from the given value, that is, at x_{i-n} and x_{i+n}, the membership value is zero (Fig. A1).

Another aspect which can be considered in the fuzzy set approach is the method of converting the universe of discourse into linguistic partitions. For example, the whole range of heights can be divided into very short, short, very medium, medium, very tall, tall, etc., as shown in Fig. A2.

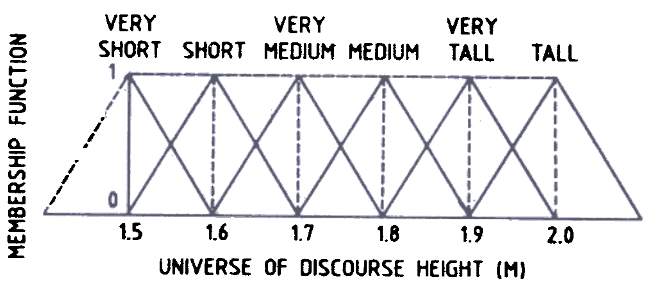

Fig. A2

The advantage in these linguistic divisions with a suitably selected transition is that, given any intermediate height or member in the universe of discourse, it can be classified as belonging to any of the above described linguistic hedges by virtue of its membership function. For example, a member of 1.625 m height has a membership function of 0.75 in the short category and membership function of 0.25 in the very medium category. Hence this member can be said to belong more to short category.